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EFFECT OF REYNOLDS NUMBER ON SLOSH DAMPING BY FLAT RING BAFFLES

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ABSTRACT

This paper examines the existing slosh data for flat ring baffles to define the effect of Reynolds number on damping. For this purpose, the drag coefficient of the baffle is presented in terms of Reynolds number. Results show that the drag coefficient increases sharply as the Reynolds number approaches zero. This implies that, for very low Reynolds numbers such as those encountered under low g, slosh damping by ring baffles will be significantly increased.

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AERO-ASTRODYNAMICS LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

DEFINITION OF SYMBOLS

Symbol	Definition
A	tank radius
C_D	baffle drag coefficient
d	baffle depth
g	acceleration level
g_o	acceleration due to gravity at earth's surface (9.8 m/sec^2)
h	fluid depth
NDV	normalized damping value
P_d	nondimensional period parameter
r	radius
Re	Reynolds number suggested in this paper
Re_{Miles}	Reynolds number suggested by Miles
W	baffle width
z	coordinate
ζ	damping ratio
ζ_{exp}	experimental damping ratio
η_w	maximum wave amplitude at wall
μ	fluid viscosity
ρ	fluid density

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SUMMARY

This paper examines the existing slosh data for flat ring baffles to define the effect of Reynolds number on damping. For this purpose, the drag coefficient of the baffle is presented in terms of Reynolds number. Results show that the drag coefficient increases sharply as the Reynolds number approaches zero. This implies that, for very low Reynolds numbers such as those encountered under low g, slosh damping by ring baffles will be significantly increased.

I. INTRODUCTION

The problem of predicting slosh damping values under low gravity conditions has become one of immediate concern to the designers of space vehicle attitude control systems. Intuitively, one might expect damping to be influenced by Reynolds number, especially in the extremely low Reynolds number range. Since the characteristic velocity is a function of gravity, propellant sloshing under low g is characterized by low Reynolds numbers. This paper defines the effect of Reynolds number upon damping, using currently available data. Once an adequate description of this effect has been obtained, it may be possible to develop from Miles' damping law a satisfactory low g damping law.

II. REVIEW OF PREVIOUS OBSERVATIONS

For ordinary rocket propellants under the influence of large gravity forces, slosh damping has generally been considered to be independent of Reynolds number. This conclusion was reached by a number of early investigators, and subsequently, no systematic review of damping data in terms of Reynolds number was ever conducted. Miles [1] concluded that the flow about baffles in large tanks was likely to be fully turbulent. He based this conclusion on the drag coefficients measured by Keulegan and Carpenter [2] for a flat plate in an oscillating fluid. Their results showed drag coefficient to be relatively independent of Reynolds number in the range $5 \times 10^3 < Re < 14 \times 10^3$. However, these

data did appear to be strongly dependent upon a nondimensional period parameter. For flow about ring baffles in cylindrical tanks, Miles developed the following expressions for Reynolds number and period parameters.

$$Re_{Miles} = 1.10W \left\{ \frac{\sinh\,[1.84(\frac{h-d}{A})]}{\sinh\,(h/A)} \right\} \sqrt{g/A}\ \frac{\eta_w}{\mu}\ \rho \qquad (1)$$

$$\text{Period Parameter} = \frac{\pi}{W/A}\ e^{-1.84d/A}\ (\eta_w/A). \qquad (2)$$

In developing his damping equation, Miles ignored the effects of Reynolds number, but he did incorporate an empirical expression for drag coefficient in terms of this period parameter. When the resulting equations were checked against experimental results, they appeared to correlate very well [3]. As a result, this expression has been widely used to predict damping by flat ring baffles. For a single submerged baffle, this expression becomes

$$\zeta = 2.83e^{-4.60(d/a)}\ [2W/A - (W/A)^2]^{3/2}\ (\eta_w/A)^{1/2}. \qquad (3)$$

Abramson and Ransleben [4] considered the problem of simulating Reynolds numbers using small model tanks and ordinary fluids. They concluded that damping was dependent upon Reynolds number and that Reynolds number must be simulated if tests in small tanks are to produce valid results.

III. CURRENT INVESTIGATION

To establish the relationship between damping and Reynolds number, a considerable amount of data was reviewed. Figure 1 shows the tank configuration under discussion here. A thin, flat ring baffle is located at sufficient depth to remain submerged at all times (i.e., $\eta_w < d$). Also, it is assumed for all cases that $h/A > 1.0$. Since the previous comparisons had dealt with the drag coefficient

rather than damping, it was decided to represent these data in the same manner. According to Miles, the damping is given by

$$\zeta = \left[.5e^{-5.52(d/A)}\right]\left[\frac{\eta_w}{A}\left(2W/A - W^2/A^2\right)\right] C_D, \tag{4}$$

or, for our purpose,

$$C_D = \frac{\zeta_{exp}}{[.5e^{-5.52(d/A)}](W/A)(2 - W/A)\ \eta_w/A}. \tag{5}$$

Since the period parameter was found to be important in Reference 2, it seemed appropriate to consider it also. All experimental data used in these comparisons were taken from References 3, 5, and 6.

In figure 2, the drag coefficient of the baffle is shown as a function of Reynolds number as given in equation (1). Although the data show some scatter, the overall trend indicates a higher drag coefficient for lower Reynolds numbers. Variation of drag coefficient with period parameter is shown in figure 3. It appears that C_D increases with a decreasing period parameter. The line indicated in figure 3 represents the empirical expression for C_D used by Miles. Several other combinations for Reynolds number were considered, one of which is shown in figure 4. For this one, the characteristic length was obtained by dividing the baffle area by the baffle width. The Reynolds number thus produced has the form:

$$Re = .55\ \frac{[2WA - W^2]}{W}\left\{\frac{\sinh\ [1.84(\frac{h - d}{A})]}{\sinh\ (h/A)}\right\}\sqrt{g/A}\ \frac{\eta_w}{\mu}\ \rho. \tag{6}$$

As indicated in figure 4, this improved considerably the correlation of the various data points. It appears that a peak of some sort occurs at $Re = 1.5 \times 10^5$. This region is shown in greater detail in figure 5. The lines shown are faired curves through the data. Notice that using this Reynolds number causes these peaks to line up very well. Figure 6 shows the same information as figure 4, but plotted on a log scale. The drag coefficient seems to remain constant with Reynolds number down to about 2×10^5. After this point, it increases sharply.

It is interesting to compare the data in figures 2, 3, and 4 with the results from reference 2, shown in figures 7 and 8. Figure 7, presenting drag coefficient as a function of period parameter, indicates the same trend as figure 3. Figure 8, showing the drag coefficient as a function of Reynolds number, according to this line of reasoning should be similar to figures 2 and 4. It is not, and the reason for this discrepancy is not obvious. Since the data in figure 8 seem to be dependent on Reynolds number when the plate width, W, is held constant, some geometric factor may have been ignored.

There is one weakness in the data so far presented. In these tests, no attempt was made to vary Reynolds number while holding the period parameter constant. To establish some means for evaluating the relative importance of these two parameters, another nondimensional quantity, the normalized damping value, was introduced. This was obtained by dividing the experimental damping value by the predicted value from equation (3). Thus,

$$NDV = \frac{\zeta_{exp}}{2.83e^{-4.60(d/A)}\left[2W/A - (W/A)^2\right]^{3/2}\left(\eta_w/A\right)^{1/2}} . \qquad (7)$$

Figure 9 shows NDV as a function of the Reynolds number. If Miles' expression for C_D in terms of period parameter is correct, NDV should be a function of only Reynolds number. The lines shown in figure 9 were obtained from a least squares curve fit of the data and apply in the regions indicated. Increased damping at low Reynolds numbers is at least suggested by these data.

As mentioned previously, low Reynolds numbers seem most likely to occur under low gravity conditions when fluid velocities are very small. Some typical Reynolds numbers for the liquid hydrogen tank of a Saturn S-IVB stage are shown in figure 10. Since the design value of g/g_0 for this vehicle is approximately 2×10^{-5}, it appears to be in the region of very high damping. This is particularly true when the amplitude is very small.

IV. CONCLUSIONS

The data reviewed show that the drag coefficient of the baffle increases as Reynolds number decreases and decreases as period parameter increases. If the influence of Reynolds number is insignificant, as suggested by Miles, then baffle damping under low gravity will be

described by the expression used for high gravity. However, if the effect of Reynolds number is really considerable, baffle damping should increase with decreasing gravity level. A conclusion regarding the relative importance of these two effects cannot be reached using the data reviewed, since the two parameters, Reynolds number and period parameter, were not varied independently. Future experimental work is expected to yield this information.

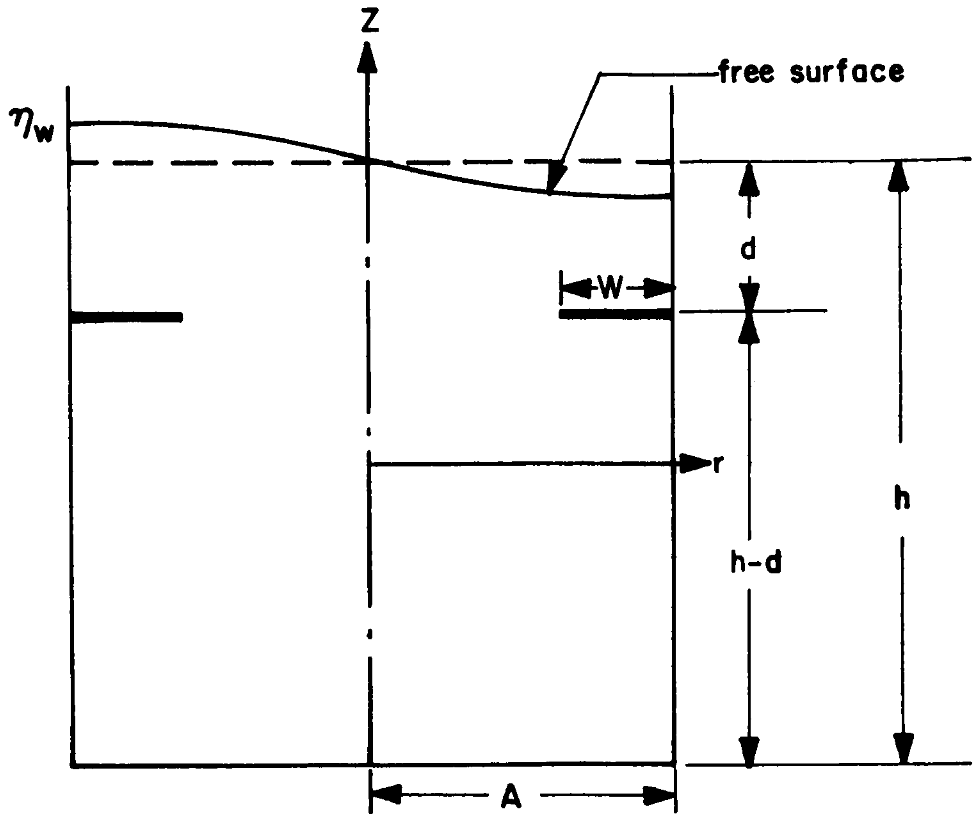


FIGURE 1

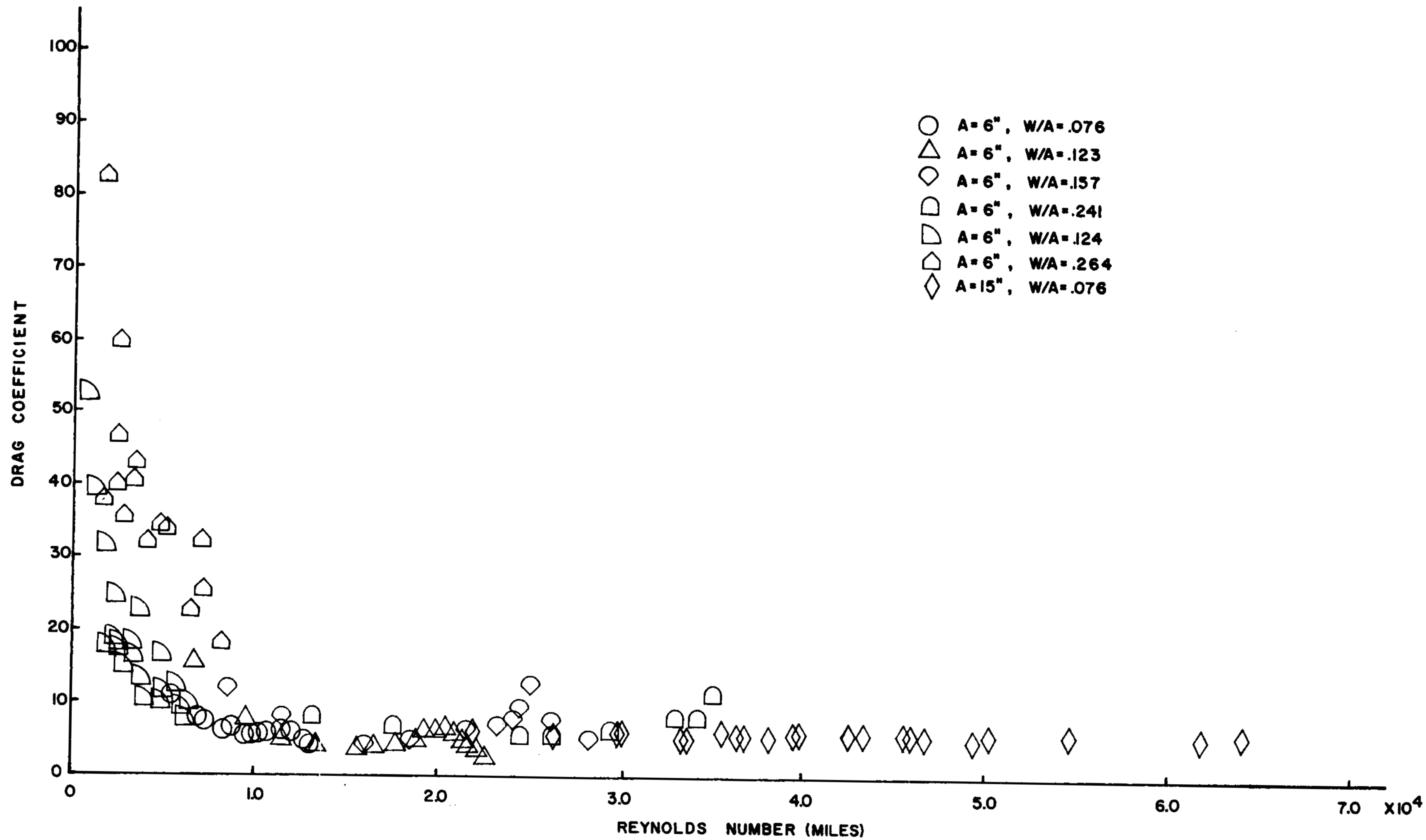
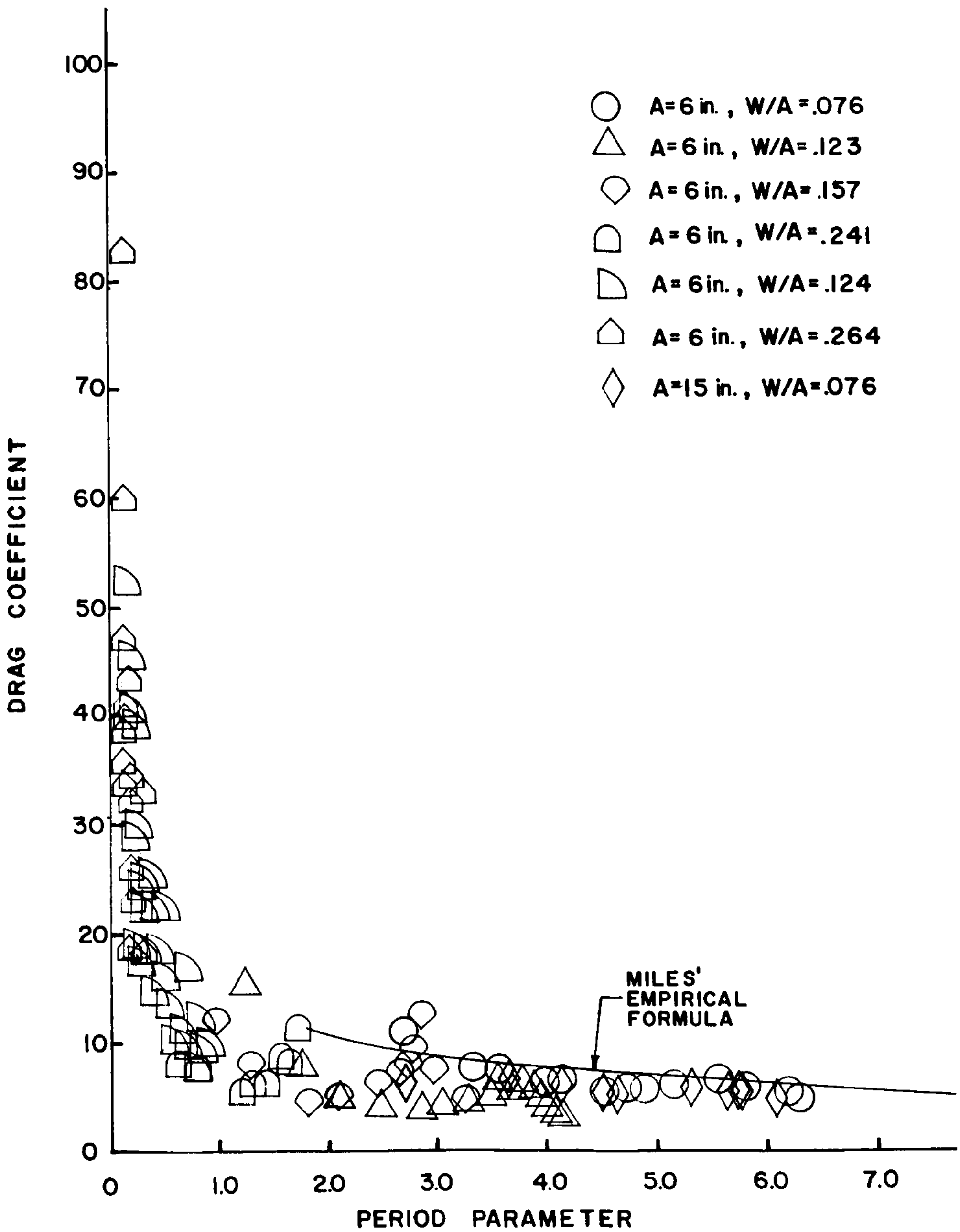

A = 6", W/A = .076
A = 6", W/A = .123
A = 6", W/A = .157
A = 6", W/A = .241
A = 6", W/A = .124
A = 6", W/A = .264
A = 15", W/A = .076
DRAG COEFFICIENT
REYNOLDS NUMBER (MILES)
X10^4

FIGURE 2



100
90
80
70
60
50
40
30
20
10
0
DRAG COEFFICIENT
A=6 in., W/A=.076
A=6 in., W/A=.123
A=6 in., W/A=.157
A=6 in., W/A=.241
A=6in., W/A=.124
A=6 in., W/A=.264
A=15 in., W/A=.076
MILES'
EMPIRICAL
FORMULA
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
PERIOD PARAMETER

FIGURE 3

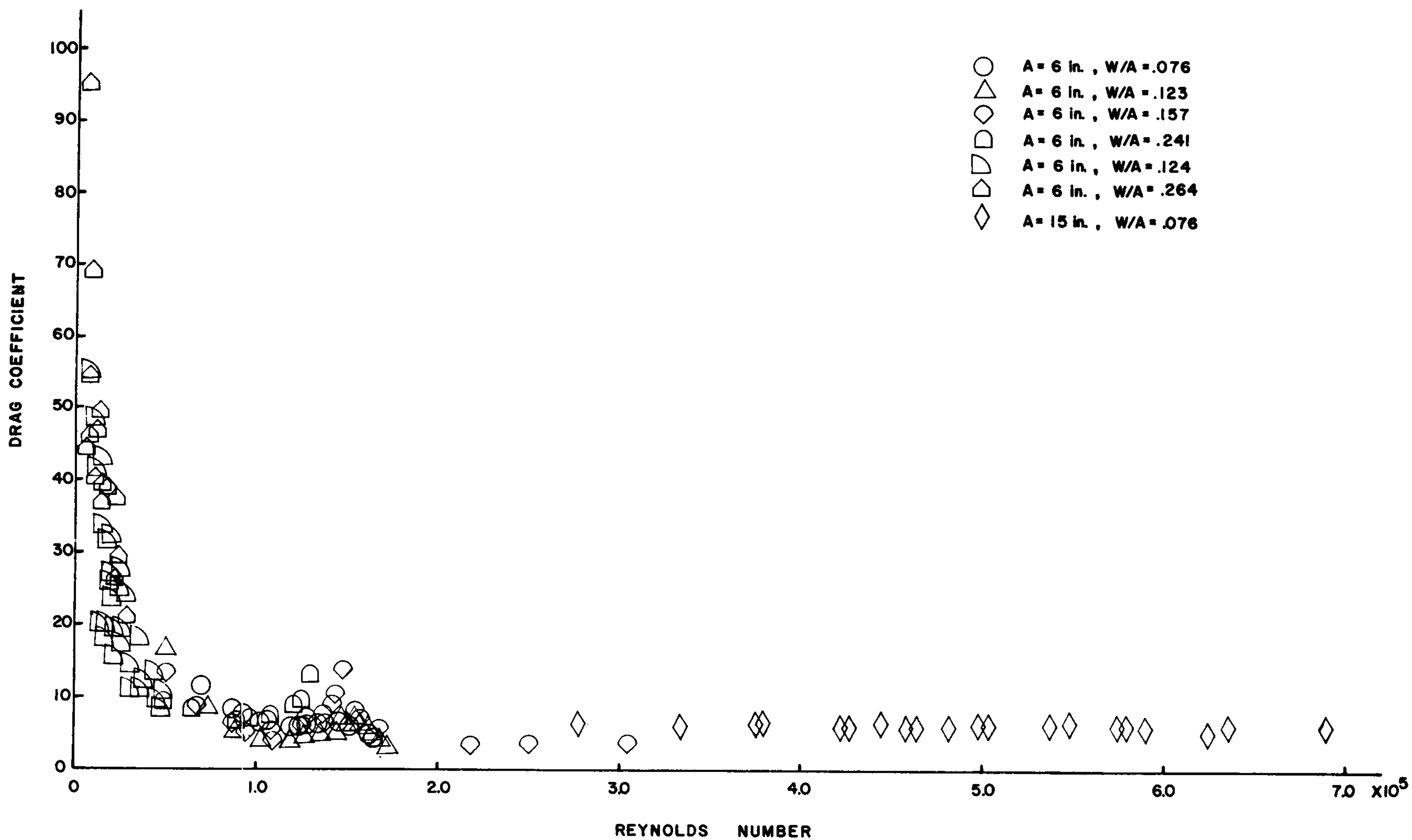
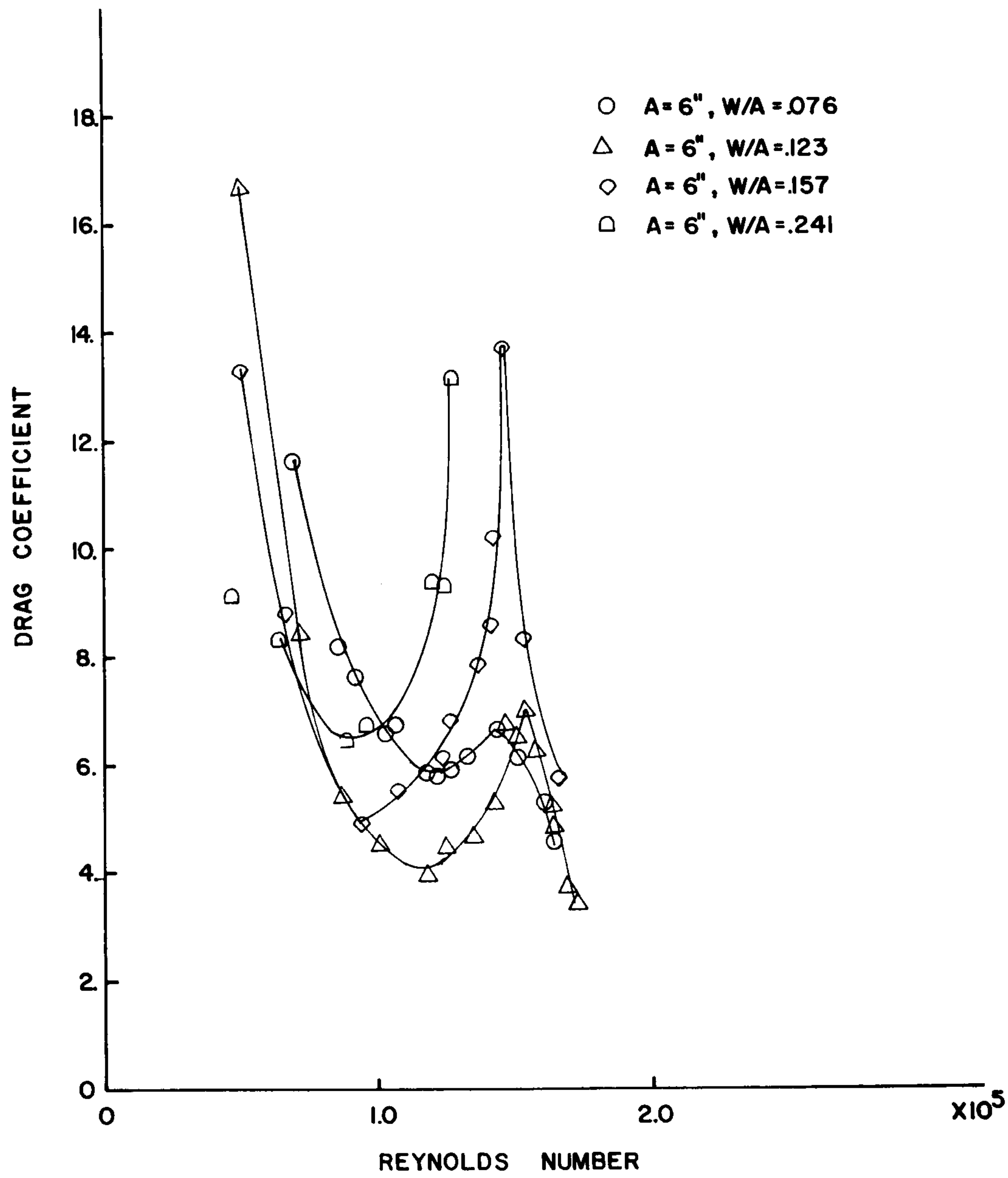

DRAG COEFFICIENT
100
90
80
70
60
50
40
30
20
10
0
REYNOLDS NUMBER
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0 X10[5]
A = 6 in. , W/A = .076
A = 6 in. , W/A = .123
A = 6 in. , W/A = .157
A = 6 in. , W/A = .241
A = 6 in. , W/A = .124
A = 6 in. , W/A = .264
A = 15 in. , W/A = .076

FIGURE 4



A= 6", W/A =.076
A = 6", W/A =.123
A= 6", W/A=.157
A= 6", W/A =.241
18.
16.
14.
12.
10.
8.
6.
4.
2.
0
DRAG COEFFICIENT
0
1.0
2.0
X10^5
REYNOLDS NUMBER

FIGURE 5

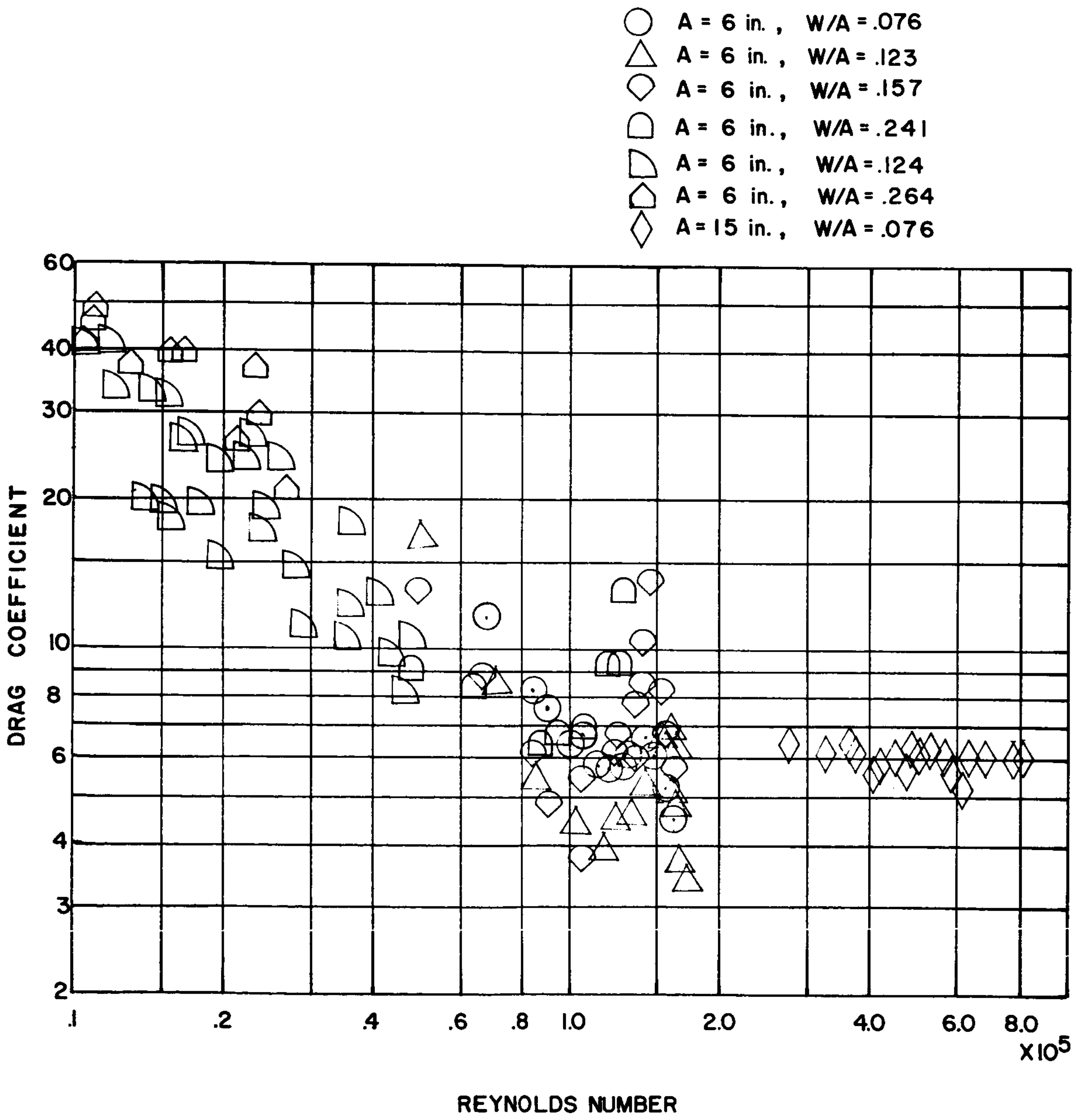

A = 6 in. , W/A = .076
A = 6 in. , W/A = .123
A = 6 in. , W/A = .157
A = 6 in., W/A = .241
A = 6 in., W/A = .124
A = 6 in., W/A = .264
A = 15 in., W/A = .076
60
40
30
20
10
8
6
4
3
2
DRAG COEFFICIENT
.1
.2
.4
.6
.8
1.0
2.0
4.0
6.0
8.0
X10^5
REYNOLDS NUMBER

FIGURE 6

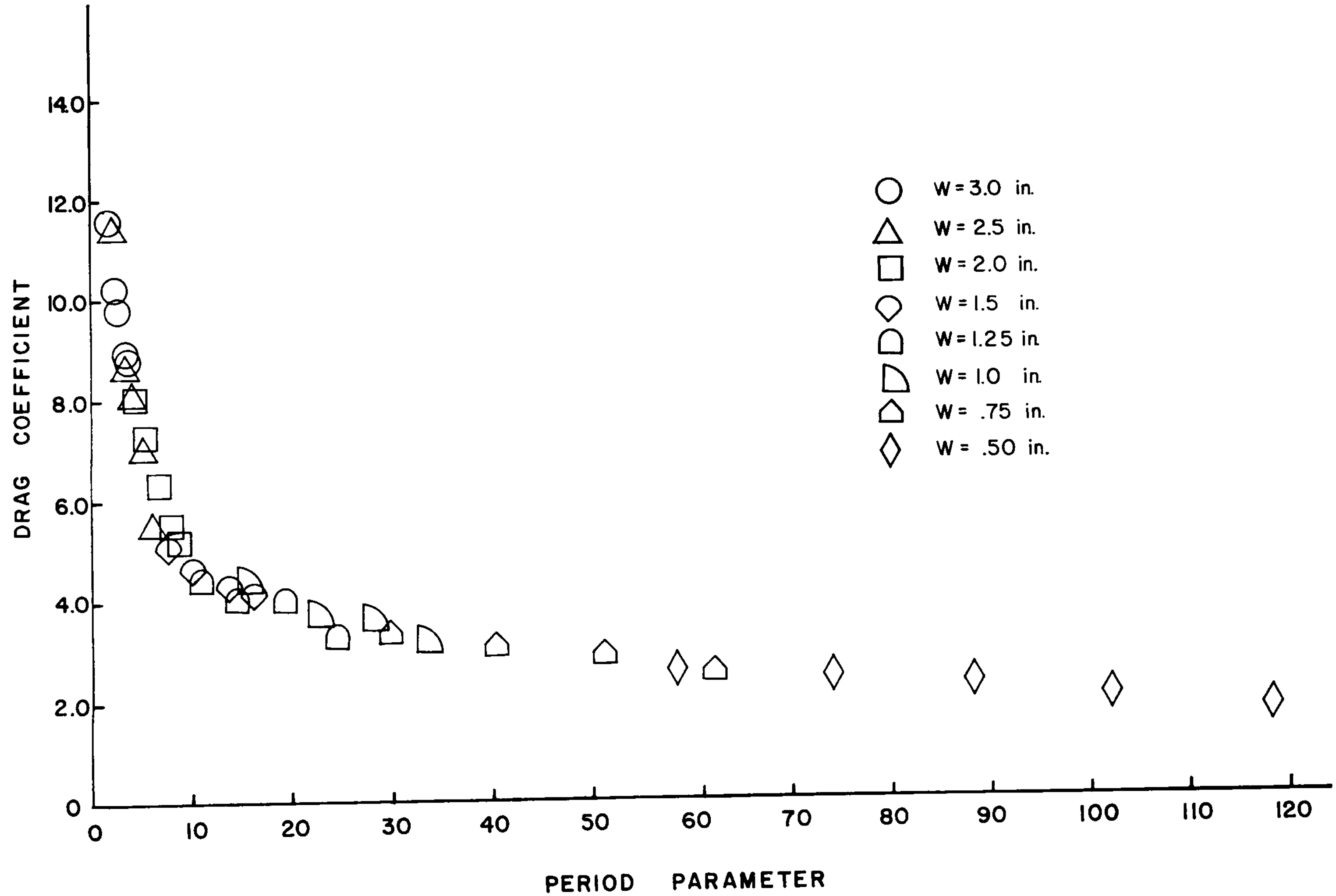

14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
DRAG COEFFICIENT
0
10
20
30
40
50
60
70
80
90
100
110
120
PERIOD PARAMETER
W = 3.0 in.
W = 2.5 in.
W = 2.0 in.
W = 1.5 in.
W = 1.25 in.
W = 1.0 in.
W = .75 in.
W = .50 in.

FIGURE 7

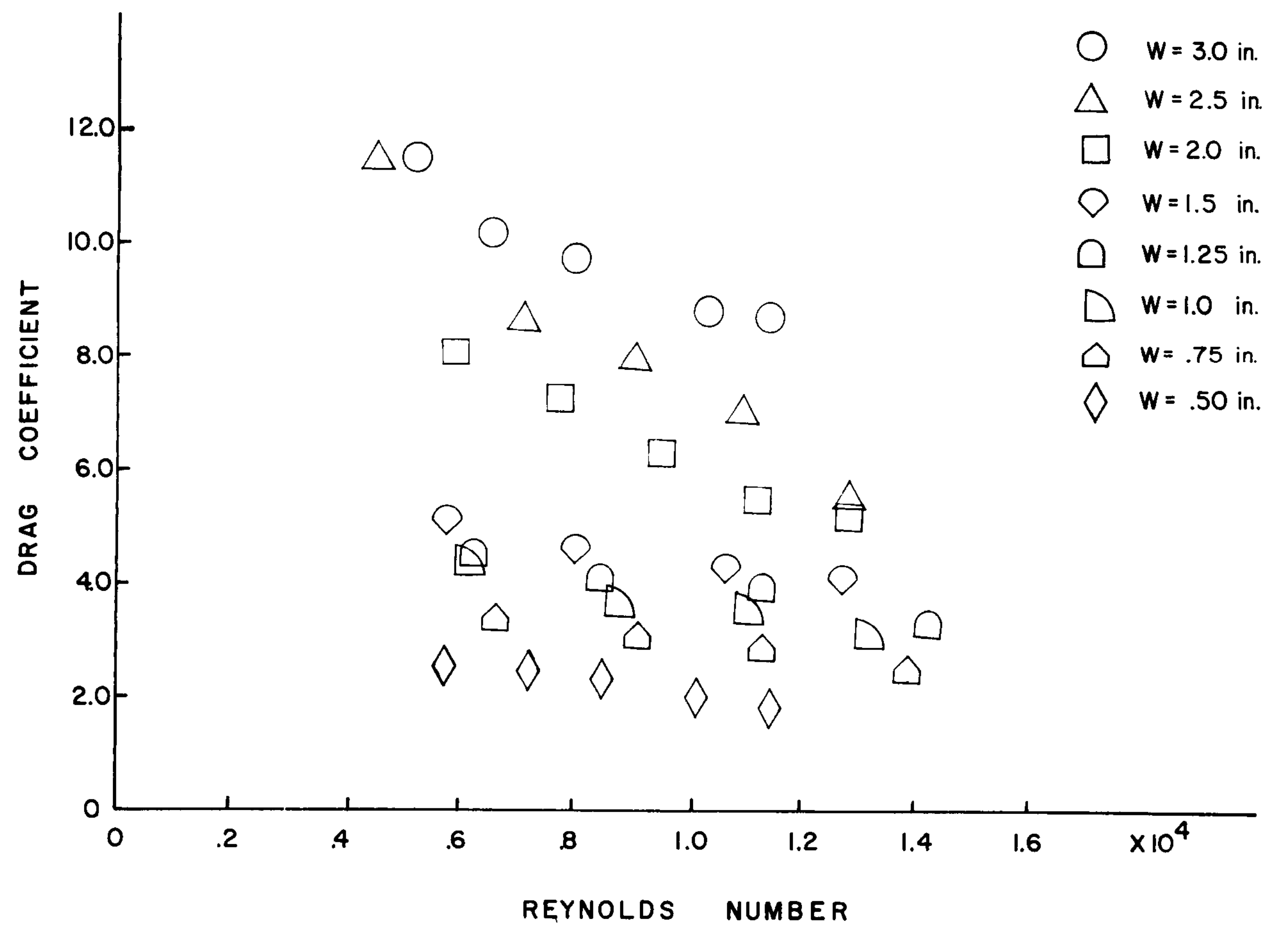

W = 3.0 in.
W = 2.5 in.
W = 2.0 in.
W = 1.5 in.
W = 1.25 in.
W = 1.0 in.
W = .75 in.
W = .50 in.
DRAG COEFFICIENT
12.0
10.0
8.0
6.0
4.0
2.0
0
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
X 10^4
REYNOLDS NUMBER

FIGURE 8

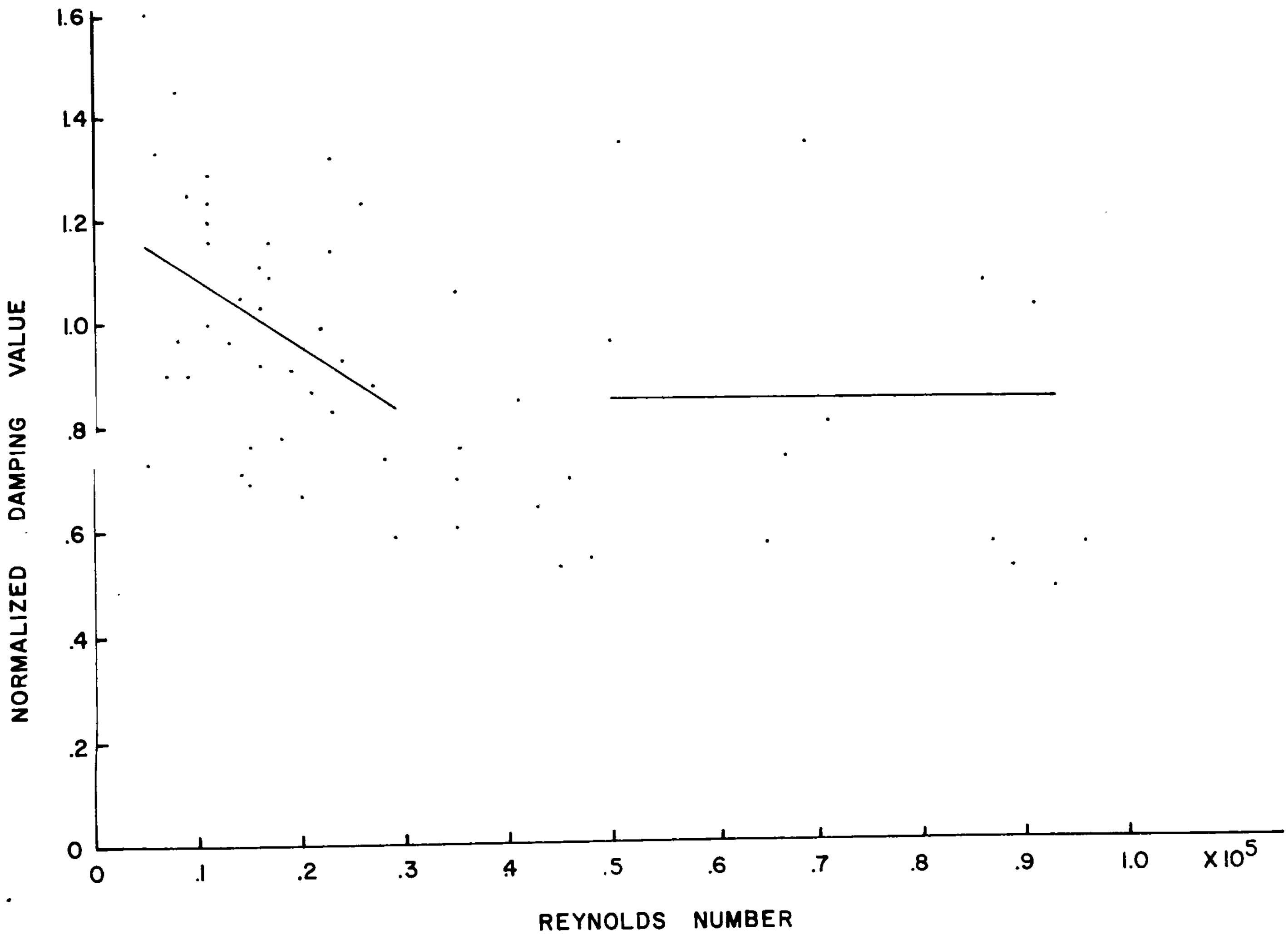

1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
NORMALIZED DAMPING VALUE
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
X 10^5
REYNOLDS NUMBER

FIGURE 9

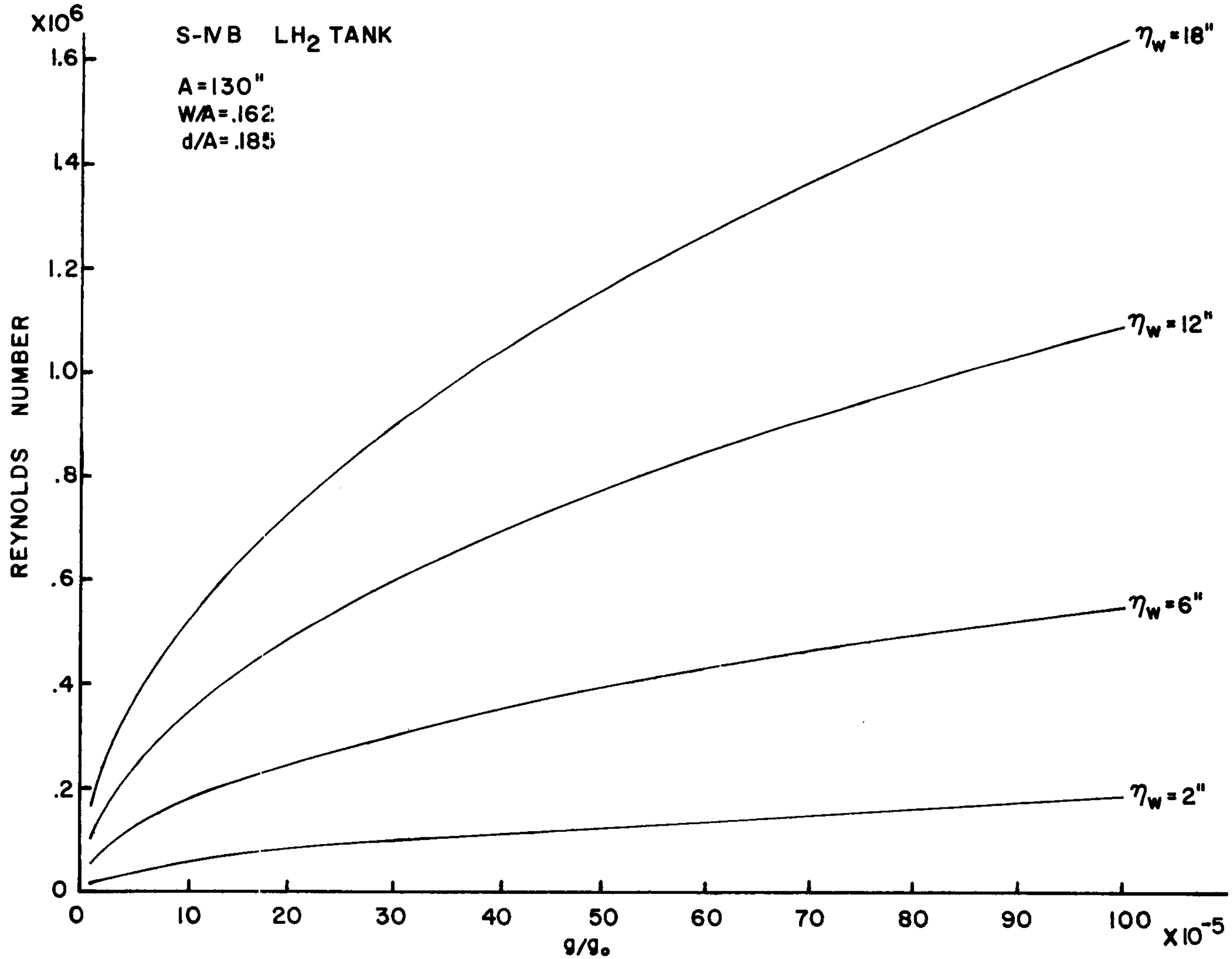

S-IVB LH$_2$ TANK
A = 130"
W/A = .162
d/A = .185
REYNOLDS NUMBER
X10^6
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
η_w = 18"
η_w = 12"
η_w = 6"
η_w = 2"
0
10
20
30
40
50
60
70
80
90
100
X10^{-5}
g/g$_o$

FIGURE 10

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This document has also been reviewed and approved for technical accuracy.

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